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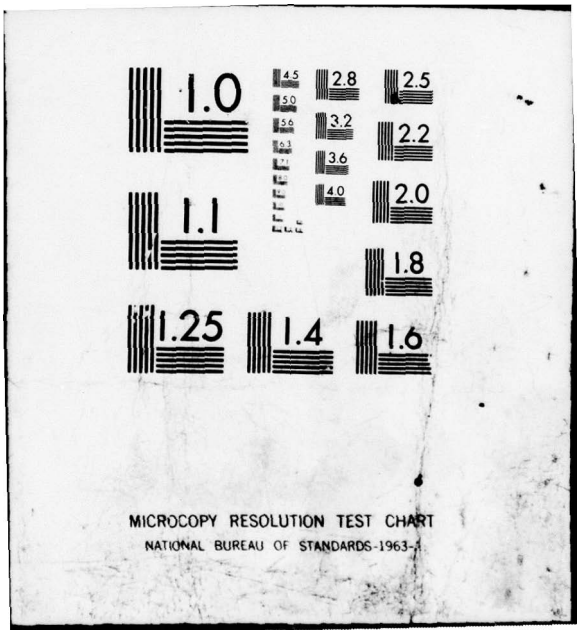
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Electromagnetic Fields in Nonuniform Multilayered Structures with Engineering Applications

FINAL REPORT–ARO 12247-EL

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UNIVERSITY OF NEBRASKA

RESEARCH SERVICE UNL ENGINEERING TECHNOLOGY TEACHING

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LEVEL II

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Final Report

ARO 12247-EL

January 1979

by

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ABSTRACT

The recent impetus to produce rigorous solutions to more realistic models of pertinent propagation problems, over a wide frequency range, has generated the need to derive full wave solutions to problems of radio wave propagation in dispersive, inhomogeneous, anisotropic and dissipative media with irregular boundaries. The considerable growth in civil and military interest in the development of more reliable systems for communication, detection, navigation and positioning, the potential for developing radio wave methods for remote sensing and the need to develop secure hardened communication systems have contributed much to this renewed interest. These developments have been paralleled by remarkable advances that have been made in the availability of high powered, very low frequency electromagnetic sources as well as the availability of transmitters operating at optical frequencies. The ready access to large, versatile digital computers has made it possible to employ the rigorous full wave approach to obtain numerical solutions to a wide class of important problems which have hitherto been either ignored or over-idealized in order to reduce them to tractable problems.

The results of these investigations have been presented in 50 technical articles which include published manuscripts, computer program papers and invited and contributed papers at international conferences. In addition, an interim Technical Report and seven semiannual Progress Reports were submitted to the U. S. Army Research Office.

Table of Contents

1. Introduction

Objective and motivation for the basic research and its engineering relevance.

The recent impetus to produce rigorous solutions to more realistic models of pertinent propagation problems, over a wide frequency range, has generated the need to derive full wave solutions to problems of radio wave propagation in inhomogeneous anisotropic media with irregular boundaries. The considerable growth in civil and military interest in the development of more reliable systems for communication, detection, navigation and positioning, the potential for developing radio wave methods for remote sensing and the need to develop secure hardened communication systems have contributed much to this renewed interest. These developments have been paralleled by remarkable advances that have been made in the availability of high powered, very low frequency electromagnetic sources as well as the availability of transmitters operating at optical frequencies. The ready access to large, versatile digital computers has made it possible to employ the rigorous full wave approach to obtain numerical solutions to a wide class of important problems which have hitherto been either ignored or over-idealized in order to reduce them to tractable problems.

2. Analytical and numerical techniques used and application of the findings to engineering problems

For the purpose of the full wave analyses it was necessary to develop generalized field transforms that provide the basis for the complete expansions for the electromagnetic fields in irregular multilayered structures with varying thickness and electromagnetic parameters[2]. These complete expansions consist of the vertically and horizontally polarized radiation fields, lateral waves and guided surface waves of the multilayered structure. The generalized field transforms are used to reduce Maxwell's equations, in conjunction with the associated exact boundary conditions for the electromagnetic fields, into sets of first order coupled differential equations for the forward and backward travelling wave amplitudes.[3],[6]

The full wave solutions are not restricted by frequency considerations, nor are they limited by often used approximate effective boundary conditions. Furthermore, rigorous methematical techniques are employed to implement the differentiation of the complete field expansion which do not necessarily converge uniformly at the irregular boundaries.

Computer programs have been developed to numerically solve the coupled differential equations. Thus the solutions obtained using the full wave approach can be readily used by engineers who are not necessarily familiar with the analytical techniques used in the analysis.[16],[21],[22],[24],[33]

Recently full wave solutions have been derived for the scattered radiation fields from rough surfaces with arbitrary slope and electromagnetic parameters.[31] These solutions bridge the wide gap that exists between the perturbational solutions for rough surfaces with small slopes and the quasi-optics solutions. Thus it is shown for example, that for good conducting boundaries the backscattered fields which are dependent on the polarization of the incident and

the scattered fields at low frequencies, become independent of polarization at optical frequencies. These solutions are consistent with reciprocity, energy conservation and duality relations in electromagnetic theory. Since the full wave solutions account for upward and downward scattering, shadowing and multiple scatter are considered. Applications to periodic structures and random rough surfaces are also presented.

To analyze problems of propagation through inhomogeneous anisotropic media such as the ionosphere, Maxwell's equations are transformed into ordinary differential equations for the four characteristic waves in the medium. The transformations used in the analysis are suitable for regions of strong coupling between the characteristic waves.[1],[5],[8],[9],[10],[15],[23] The solutions are shown to satisfy energy conservation and reciprocity relationships. This approach has also been applied to problems of communication via inhomogeneous, multimode optical fibers with minimum dispersion,[12],[26] and to determine the reflection and transmission of transient signals in the presence of the ionosphere.[17],[25],[30]

Several computer programs on propagation in irregular waveguides, optical fibers and inhomogeneous and isotropic media have also been published in the technical literature to assist the engineer in directly applying the results of our investigations.[7],[13],[14],[28],[29],[32],[34],[35]

Both analytical and numerical techniques are developed to determine the transient electromagnetic response from nonuniform layered structures. This work can be used to determine irregular medium efforts on navigational and positioning systems and can be applied to problems of remote sensing.[4],[11],[18],[19],[20] Time domain measurements have been conducted to determine microwave radiation effects on biological materials.[27]

In addition to publications in the technical literature[1] through,[35] the principal investigator has presented invited and contributed papers at several international conferences[36] through.[50]

3. Description of research and results

Detailed description of the analytical and numerical techniques used in these investigations and applications to engineering and technology are given in the reprints and preprints of the technical papers submitted with the report. (See List of Publications, Sections 6a and 6b).

An interim (320 page) Technical Report 0075-USARO-01 and seven semi-annular Progress Reports were submitted by the principal investigator to the U.S. Army Research Office over the period of the grant.

4. Personnel supported by this project

In addition to the principal investigator, Ezekiel Bahar, the following persons: M. Fitzwater, B. S. Agrawal, S. Lai, J. P. Chaudhary, W. A. Currie
s and G. A. Kriegsmann, were assigned at various times to this project.

M. Fitzwater and B. S. Agrawal earned the Master of Science Degrees in Electrical Engineering at the University of Nebraska while employed on the project.

5. Acknowledgments

The author wishes to thank F. H. Reder, F. Schwering and J. Mink for their interest and stimulating discussions.

The basic research related to the development of the full wave analytical solutions were supported in part by a grant from the National Science Foundation. Additional support was provided by the Engineering Research Center and the Research Council at the University of Nebraska.

6. List of Publications by the Principal Investigator During Period of ARO Grant

(a) Publications in Technical Journals

(1) "Fields of an Electric Line Source Parallel to an Inhomogeneous Dielectric Layer with Critical-Coupling Regions," with G. Govindarajan and B. S. Agrawal, Radio Science, Vol. 10, No. 2, February 1975, pp. 197-204.

(2) "Field Transforms for Multilayered Cylindrical and Spherical Structures of Finite Conductivity," Canadian Journal of Physics, Vol. 53, No. 11, 1975, pp. 1078-1087.

(3) "Propagation in Irregular Multilayered Cylindrical Structures of Finite Conductivity--Full Wave Solutions," Canadian Journal of Physics, Vol. 53, No. 11, 1975, pp. 1088-1096.

(4) "EM Fields in Nonuniform Multilayered Structures Steady-State and Loran C Pulse Excitation," Precision Time and Time Interval Proceedings, X-814-76-45, December 1975, pp. 475-493.

(5) "Generalized Characteristic Functions for Simultaneous Linear Differential Equations with Variable Coefficients Applied to Propagation in Inhomogeneous Anisotropic Media," Canadian Journal of Physics, Vol. 54, No. 3, 1976, pp. 301-306.

(6) "Electromagnetic Waves in Irregular Multilayered Spheroidal Structures of Finite Conductivity--Full Wave Solutions," Radio Science, Vol. 11, No. 2, 1976, pp. 137-147.

(7) "Transition Section Spurious Mode Program," with G. Govindarajan, IEE Proceedings, Vol. 123, No. 4, April 1976, p. 298.

(8) "Excitation of Horizontally Polarized Waves in Critical-Coupling Regions Where the Permittivity Gradient Approaches Zero--Full Wave Solutions," Journal of Mathematical Physics, Vol. 17, No. 6, June 1976, pp. 929-936.

(9) "Horizontally Polarized Waves in Inhomogeneous Media--Energy Conservation and Reciprocity Relationships," with B. S. Agrawal, IEEE Transactions on Antennas and Propagation, Vol. AP-24, No. 4, July 1976, pp. 506-575.

(10) "Vertically Polarized Waves in Inhomogeneous Media with Critical Coupling Regions, Energy Conservation and Reciprocity Relationships," with B. S. Agrawal, Radio Science, Vol. 11, No. 11, November 1976, pp. 885-896.

(11) "Effects of Irregular Medium on Navigation and Positioning Systems--Full Wave Solutions," Advisory Group for Aerospace Research and Development--Propagation Limitations of Navigational and Positioning Systems, December 1976, Conference Proceedings, No. 209, 10, pp. 1-16.

(12) "A Generalized WKB Approach to Propagation in Inhomogeneous Dielectric Waveguides," with B. S. Agrawal, Special Issue of Radio Science on Communications Via Optical Fibers and Integrated Optics, Vol. 12, No. 4, July-August 1977, pp. 611-618.

(13) "Waveguide Bend Spurious Mode Program," with G. Govindarajan, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-25, No. 8, August 1977, p. 713.

(14) "Propagation of Horizontally Polarized Waves Through $q^2(x)$ Profiles with Simple Zeros," with B. S. Agrawal, IEEE Transactions on Antennas and Propagation, Vol. AP-25, No. 5, September 1977, p. 727.

(15) "Transmission of Horizontally Polarized Waves and Trapped Waveguide Modes in Inhomogeneous Media," with B. S. Agrawal, IEEE Transactions on Antennas and Propagation, Vol. AP-25, No. 6, November 1977, pp. 807-813.

(16) "Coupling Between Guided Surface Waves, Lateral Waves and the Radiation Fields by Rough Surfaces--Full Wave Solutions," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-25, No. 11, November 1977, pp. 923-931.

(17) "Effects of the Ionosphere on Navigational and Positioning Systems--Full Wave Solutions," with B. S. Agrawal, Proceedings of the Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems, NRL and the Office of Naval Research, S6-1, pp. 1-12, January 1978.

(18) "Transient Electromagnetic Response from Nonparallel Stratified Models of the Earth's Crust--Part I Scattered Radiation Field," Radio Science, Vol. 13, No. 1, January-February 1978, pp. 1-10.

(19) "Transient Electromagnetic Response from Nonparallel Stratified Models of the Earth's Crust--Part II The Scattered Surface Wave," Radio Science, Vol. 13, No. 1, January-February 1978, pp. 11-20.

(20) "Transient Electromagnetic Response from Irregular Models of the Earth's Surface," Radio Science, Vol. 13, No. 2, March-April 1978, pp. 345-355.

(21) "Full Wave and Physical Optics Solutions for Scattered Radiation Fields by Rough Surfaces--Energy and Reciprocity Relationships," IEEE Transactions on Antennas and Propagation, Vol. AP-26, No. 4, July 1978, pp. 603-614.

(22) "Rough Surface Scattering of Horizontally Polarized Waves and Polarization Dependence of Backscatter Cross-Section," with G. G. Rajan, Radio Science, January-February 1979.

(23) "Generalized Characteristic Functions Applied to Propagation in Bounded Inhomogeneous Isotropic Media," with B. S. Agrawal, Journal of Atmospheric and Terrestrial Physics--in press.

(24) "Depolarization and Scattering of Electromagnetic Waves by Irregular Boundaries for Arbitrary Incident and Scatter Angles--Full Wave Solutions," with G. G. Rajan, IEEE Transactions on Antennas and Propagation--in press.

(25) "Ionosphere Effects on Navigational and Positioning Signals--Full Wave Solutions," with B. S. Agrawal, IEEE Transactions on Antennas and Propagation--in press.

(26) "Application of Generalized Characteristic Vectors to Problems of Propagation in Cladded Inhomogeneous Dielectric Waveguides," with B. S. Agrawal, IEEE Transactions on Microwave Theory and Technology--in press.

(27) "Time Domain Measurements for Determination of Dielectric Properties of Agricultural Materials," with B. P. Kwok and S. O. Nelson, IEEE Transactions on Instrumentation and Measurement--in press.

(28) "Vertically Polarized Waves in Inhomogeneous Media with Critical Coupling Regions," with B. S. Agrawal, submitted for review.

(29) "Propagation of Horizontally Polarized Waves Through $q^2(z)$ Profiles with One or Two Neighboring Simple Zeros," with B. S. Agrawal, submitted for review.

(30) "Distortion and Depolarization by the Ionosphere of L Band Signals Coded by Phase Reversals: Full Wave Solutions," with B.S. Agrawal, submitted for review.

(31) "Full Wave Solutions for the Scattered Radiation Fields from Rough Surfaces with Arbitrary Slope and Frequency," submitted for review.

(32) "Waveguide Modes in Inhomogeneous Media," with B. S. Agrawal, submitted for review.

(33) "Computations of the Transmission and Reflection Scattering Coefficients in an Irregular Spheroidal Model of the Earth-Ionosphere Waveguide," submitted for review.

(34) "Propagation of EM Waves in Inhomogeneous Anisotropic Media," with B. S. Agrawal, submitted for review.

(35) "Radio Waves in an Irregular Spheroidal Model of the Earth Ionosphere Waveguide," with M. Fitzwater, submitted for review.

(b) Abstracts and Summaries of papers presented at International Conferences

(36) XVIII General Assembly of the International Union of Radio Science (URSI) Member of U.S. Delegation, Lima, Peru, August 11-19, 1975. Title of paper, "Electromagnetic Scattering from an Irregular Multilayer Model of the Earth Ionosphere Waveguide."

(37) International Union of Radio Science (URSI) Scientific Meeting at Boulder, Colorado, October 20-23, 1975. Title of paper (with M. Fitzwater) "Transient Electromagnetic Response from Nonuniform Layered Models of the Earth's Crust."

(38) International Union of Radio Science (URSI) Scientific Meeting at Boulder, Colorado, October 20-23, 1975. Title of paper (with B. S. Agrawal) "Horizontally Polarized Waves in Ionized Media with Varying Electric Density and Collision Frequency. Energy Conservation and Reciprocity Relationships."

(39) Seventh Annual Precise Time and Time Interval (PTTI) Planning Meeting (U.S. Naval Electronics, NASA and U.S. Naval Observatory) Greenbelt, Maryland, December 2-4, 1975. Invited paper "Electromagnetic Fields in Nonuniform Layered Structures. Steady State and Loran-C Excitations."

(40) International IEEE/AP-S Symposium at the University of Massachusetts, Amherst, Massachusetts, October 10-15, 1976. "Transmission of Vertically Polarized Waves and Trapped Waveguide Modes in Inhomogeneous Media with Critical Coupling Regions."

(41) International Union of Radio Science (URSI) Meeting at La Baule, France, April 28-May 6, 1977. "Transient Electromagnetic Response from Irregular Models of the Earth's Crust."

(42) International Union of Radio Science (URSI) Meeting at the University of Massachusetts, Amherst, Massachusetts, October 10-15, 1976. "Scattering by Rough Surfaces--Full Wave and Physical Optics Solutions."

(43) Symposium on Propagation Limitations on Navigation and Positioning Systems, Sponsored AGARD Electromagnetic Wave Propagation Panel Technical Meeting at Istanbul, Turkey, October 20-22, 1976. Invited to present paper on "Effects of Irregular Media on Navigation Signals--Full Wave Solutions."

(44) International IEEE/AP-S Symposium at Stanford University, Stanford, California, June 20-22, 1977. "A Generalized WKB Approach to Propagation in Inhomogeneous Dielectric Waveguides."

(45) International Union of Radio Science (URSI), Symposium at Stanford University, Stanford, California, June 22-24, 1977. "Generalized Characteristic Functions Applied to Propagation in Bounded Inhomogeneous Anisotropic Media--Reciprocity and Energy Relationships."

(46) Symposium on The Effect of the Ionosphere on Space Systems and Communications, Sponsored by the Naval Research Laboratory Space Technology Seminar Committee and the Office of Naval Research, at Washington, D.C., January 24-26, 1978. "Effects of the Ionosphere on Navigation and Positioning Systems--Full Wave Solutions."

(47) International Union of Radio Science (URSI) Symposium at the University of Maryland, May 15-19, 1978. "Computations of Mode Scattering in an Irregular Multilayered Spheroidal Model of the Earth."

(48) International IEEE/AP-S Symposium at the University of Maryland, May 15-19, 1978, "Rough Surface Scattering of Horizontally Polarized Waves and Polarization Dependence of Back Scatter Cross-Section. Full Wave Solutions."

(49) International Symposium on Optical Communication Sponsored by URSI Commission B at Helsinki, Finland, July 31-August 9, 1978. Member of official U.S. Delegation to General Assembly. Title of paper, "Application of Generalized Characteristic Vectors to Problem of Propagation in Cladded Inhomogeneous Dielectric Waveguides."

(50) International Symposium on Radio Waves and the Ionosphere Sponsored by Commission G at Helsinki, Finland, July 31-August 9, 1978. Title of paper, "Propagation of Satellite Signals Through the Ionosphere.